

# Optical Closure in Coastal Waters

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## LONG-TERM GOAL

The goal of this program is to test, validate, and refine our understanding of radiative transfer in the ocean and our ability to accurately measure ocean-optical properties with particular emphasis on coastal waters.

## OBJECTIVES

Our scientific objectives encompass both empirical and theoretical investigations. Empirical objectives are: 1) develop new instruments and methods for measuring ocean-optical properties, 2) conduct systematic coastal ocean measurements for testing closure and for characterizing optical properties and the processes related to their changes, and 3) perform laboratory experiments to investigate optical propagation phenomena in a controlled environment. Theoretical objectives are: 1) develop spectral models for scattering by marine suspensions, 2) investigate second order and other approximations to the radiative transfer equation, and 3) develop the mathematics for better understanding and modeling long-path beam propagation and radiative transfer of submerged light sources.

A final-year objective of this program was to assist in teaching the summer Ocean Optics course held at Friday Harbor, Washington.

## APPROACH

Optical closure has many facets, but it always involves the comparison of theory with measurements. Probably the most common example is the energy balance equation  $a + b = c$ , where  $a$ ,  $b$ , and  $c$  are, respectively, the absorption, total scattering, and beam attenuation coefficients. Yet even this simple equation has not been experimentally applied in the sense of closure due to historical and present limits on our ability to measure, simultaneously, these three optical coefficients. Why is it important to test an equation that we know from conservation of energy must be correct? Because there are not yet accepted standards for the calibration of instruments that measure inherent optical properties (IOP's); thus the only way currently to objectively characterize measurement accuracy of IOP's is through closure. Another example of closure involving IOP's, apparent optical properties (AOP's) and radiometric quantities is Gershun's equation, which can be expressed as  $a = KE/E_0$ , where  $K$  is the net irradiance attenuation coefficient,  $E$  is the net irradiance, and  $E_0$  is the scalar irradiance. Once again, this is another example of a well established equation that has yet to be tested in the sense of closure. Until we develop the instruments and methods to systematically test closure of at least the simple examples like these, we will not be able to establish the true accuracy of our optical property measurements.

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Part of our approach is to develop new instruments and methods, including designing experiments that can be conducted in the laboratory and at sea, for measuring optical properties in the full sense of closure. This work has involved analyzing new ways for measuring net and scalar irradiance [Maffione, 1994], developing new instruments and methods for measuring the absorption, beam attenuation, and backward-scattering coefficients [Maffione et al., 1991; 1993a; Maffione and Dana, 1997a; Dana et al., 1998], and building new types of multisensor platforms [Maffione et al., 1993b]. Perhaps the most outstanding deficiency in our ability to perform closure, as well as our ability to simply characterize the scattering properties of oceanic waters, is the lack of instrumentation for measuring the volume scattering function (VSF). I am addressing this instrument development problem on a separately funded ONR program. Another important problem associated with the VSF is its value at 180 degrees, which has direct application to oceanic lidar. To investigate this problem, which involves the closure of measurements from lidar systems and in-situ sensors, we developed an instrument called Beta Pi [Maffione and Honey, 1992]. This instrument was later modified to measure both the VSF at 180 degrees and the lidar attenuation coefficient [Maffione and Dana, 1996]. Also of interest in the investigation of closure as it relates to ocean-color remote sensing is the measurement of the backward-scattering coefficient. To address this problem, we have developed a variety of multispectral backscattering sensors and rigorous methods for their calibration [Maffione and Dana, 1997a].

## WORK COMPLETED

We accomplished the following:

1. Completed the development, testing, and calibration of new combined backscattering, absorption, and beam attenuation sensors that were also successfully transitioned into the commercial market [Dana et al., 1998].
2. Completed the development, testing, and calibration of a six wavelength backscattering sensor that also was successfully transitioned into the commercial market [Maffione and Dana, 1997a].
3. Developed new theoretical techniques for understanding long-path beam propagation and the approach to the asymptotic state of the light field created by submerged sources [Maffione, submitted].
4. Assisted in teaching the Ocean Optics summer course held at Friday Harbor, Washington.

## RESULTS

From the results of extensive Mie scattering calculations for a range of particle size distributions and refractive indices, we found that the backward scattering coefficient  $b_b$  can be accurately estimated from measurements of the VSF over a range of angles from 120 to 160 degrees [Maffione and Dana, 1997a]. For the HydroScat-6 backscattering sensor, which measures the VSF at a centroid angle of 140 degrees, the best estimate of  $b_b$  is given by  $b_b = 1.08 \times 2\pi\beta(140^\circ)$ , where  $\beta(140^\circ)$  denotes the VSF measurement at 140 degrees. The percent standard error in this estimate was 9% over a wide range of scattering calculations and there was no statistically significant dependence on wavelength. For the range of scattering calculations for realistic oceanic particles, the percent standard error was 5%. Considering that the HydroScat-6 is the only IOP instrument whose calibration is traceable to an NIST standard (namely the reflectance of Spectralon), this accuracy represents a milestone in our ability to measure IOP's.

Our Mie scattering calculations also showed that the least correlation with  $b_b$  was near and at the "end" angles 90 and 180 degrees [Maffione and Dana, 1997a]. For estimating  $b_b$  from discrete

backscattering angle measurements, the “middle” angles from about 110 to 160 degrees are best. The VSF at 180 degrees showed the highest variability with changes in particle size distribution and index of refraction and was least correlated with the VSF at all other backscattering angles. This result has important consequences to monostatic lidar systems since the backscattered signal is directly proportional to  $\beta(180^\circ)$ . In other words the lidar return signal could depend significantly on particle size distribution which is not expected to be systematically correlated with the absorption coefficient at typical lidar wavelengths, such as 532 nm. This could partly explain the calibration discrepancies often found when comparing lidar calculated attenuation coefficients with coefficients measured in situ.

An interesting theoretical result which also has consequences to oceanic lidar was my derivation of a proof that the asymptotic state is approached extremely more slowly for the light field created by an embedded source than it is for plane-wave solar illumination [Maffione, submitted]. The possibility of the existence of this phenomenon was first suggested by Maffione and Jaffe [1995], based on Monte Carlo calculations of a submerged point source. Because of the controversy created by this result, it was later checked and confirmed using an independent Monte Carlo model developed by Mobley [1996]. The theoretical proof that I derived firmly establishes the validity of this phenomenon and provides a simple formula for calculating the optical pathlength for the approach to the asymptotic state for a submerged light source based on the IOP's of the medium. Because of the equivalence of the point spread and beam spread functions, this result has important applications to oceanic lidar and underwater visibility.

Our intensive coastal optical research in Monterey Bay has resulted in an exciting empirical characterization of the modulation of scattering layers by a near-shore internal wave [Maffione et al., 1996; Maffione, 1997b]. In water as shallow as 30 m, we were able to measure scattering layers, at an average depth of 7.2 m, being modulated with a peak-to-trough amplitude of 5 m. Using the profiles of the measured IOP's as input into Hydrolight, a numerical radiative transfer model developed by Curt Mobley, we calculated that the optical modulation resulted in a maximum change in the water leaving radiance of 24% [Maffione, 1997b]. Thus, it is entirely possible that near-shore internal waves, especially those found in Monterey Bay, could be mapped with an airborne hyperspectral imager.

## IMPACT/APPLICATIONS

My work on developing instruments and methods for directly measuring spectral backscattering is already having a profound impact on ocean-color remote sensing. My work on investigating the nature of the optical properties associated with oceanic-lidar systems, and the instruments I developed for this purpose, continue to be critical to understanding oceanic-lidar signals. Indeed, perhaps the most outstanding fundamental problem in this area today is the apparent paradox that the attenuation coefficients measured by these systems is often lower than in-situ IOP measurements, and sometimes they are even lower than accepted values for pure water. My work on measuring and modeling the lidar backscattering and attenuation is beginning to shed light on this outstanding problem. My proof of the slow approach to the asymptotic state for the point spread and beam spread functions, and its confirmation through Monte Carlo modeling, has important implications to this problem. For example, it has been commonly assumed that the lidar attenuation coefficient rapidly approaches the asymptotic state, and thus it was often equated to the downwelling diffuse attenuation coefficient  $K_d$ . As pointed out above, paradoxical discrepancies often arose when comparisons were made of the lidar attenuation coefficient and *in-situ* measurements of  $K_d$ . The fact that I have now firmly established that the BSF approaches the asymptotic state extremely slowly may help resolve this problem.

## TRANSITIONS

The instruments and methods I developed (in collaboration with David Dana at HOBILabs), as part of my closure research for measuring the backward-scattering coefficient, are being used by investigators throughout the world. The list is too numerous to cite here. My closure work on oceanic lidar is being used on several Navy programs, including Magic Lantern and April Showers.

## RELATED PROJECTS

Closely related projects that I am actively involved in are:

1. April Showers and Magic Lantern oceanic lidar programs, where I provide environmental measurements and analysis of in-situ optical measurements.
2. Coastal Benthic Optical Properties (CoBOP), funded by ONR, where I am applying my optical closure methods to understanding and characterizing benthic optical properties.
3. Project funded by the U.S. Army Corps of Engineers to study the impact of dredging on light attenuation and seagrass productivity in Laguna Madre, Texas. My participation is to use my instruments, methods, and models developed under closure to investigate this problem.

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